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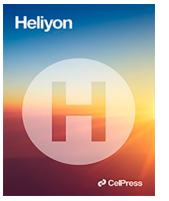

Research article

Coupling coordination degree measurement and spatial characteristics analysis of green finance and technological innovation -Empirical analysis based on China

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ABSTRACT

The coordinated development of green finance and technological innovation is a key driver of China's high-quality economic growth and therefore deserves close attention. But are green finance and technological innovation really coordinated? This study establishes a coordinating coupling system to link green finance and technological innovation. 2010–2021 is chosen as the observation period, and 31 provinces in China are selected for study. This paper uses the coupling coordination model to investigate the development of the coupling coordination of technological innovation and green finance, and discusses its spatial distribution by the Moran index. The results show that, overall, the degree of coupling coordination between green finance and technological innovation shows a consistent upward trend. The trend is particularly strong in the East. Moreover, the coordination coupling between green finance and technological innovation has the spatial effect. And it shows a binary characteristic, with a decreasing trend observed from coastal to inland regions. These results remained valid after replacing weight matrix and sample size.The above findings have important policy implications for optimising the synergistic development of green finance and technological innovation and achieving high-quality economic development.

1. Introduction

In the face of increasingly serious climate problems, the promotion of low-carbon development has become the consensus of all sectors of society [1]. As a responsible major nation, China has actively participated in discussions on global climate change and made a solemn commitment at the United Nations General Assembly. As a result, China is under unprecedented pressure to reduce carbon emissions [2], and green finance and technological innovation are seen as key mechanisms for carbon reduction. In February 2021, the State Council issued the Guiding Opinions on Green Development, which explicitly emphasised the central role of green finance and technological innovation in promoting the development of a low-carbon economy. However, restrictions on either side will affect the development of the other, hindering progress towards a low-carbon economy. How do green finance and technological innovation interact and can they coexist harmoniously? Is there a spatial dimension to this relationship and how can we improve their coordination? These are questions that warrant extensive discussion and research.

In the existing literature, there is limited research that focuses on quantifying the coordination between green finance and technological innovation, with most studies focusing on discussing concepts and motivations. First, the concept of coupling coordination

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between green finance and technological innovation. This refers to the structural coupling coordination between green finance and green technology, which includes two types of finance-technology structure and technology-finance structure [3]. The former refers to promoting green finance on technological innovation, while the latter refers to promoting technological innovation on green finance. Second, the motivation for coordinating the coupling between green finance and technological innovation. Although there is no current research on the specific motivation for this coupling coordination, factors such as resource and environmental constraints [4], government policies [5] and public sentiment [6] are recognised as shared drivers that promote the development of both green finance and technological innovation. These common drivers serve as key factors driving the coordination of green finance and technological innovation.

In conclusion, the study of the direct and spatial effects of the coupling coordination between green finance and technological innovation is of great theoretical and practical importance. However, a limited number of studies have addressed the conceptualisation and motivation of the coupling coordination between technological innovation and green finance, while research on the measurement and spatial effects of this synergy remains scarce. To address this gap, a coupling coordination model is used to assess the level of coupling coordination between green finance and technological innovation in 31 provinces across China. The spatial impact of green finance and technological innovation is then analysed.

Compared to the existing literature, this study contributes as follows: First, we measure the degree of coupling coordination between green finance and technological innovation, thereby complementing existing research. The existing literature mainly focuses on the concept of coupling coordination, neglecting its quantification. This paper aims to measure the degree of coupling coordination, thereby providing a deeper understanding of their dynamic relationship. Second, to gain a deeper understanding of the relationship between green finance and technological innovation, we establish an evaluation index system and apply the degree of coupling coordination, providing important theoretical and practical insights on the coupling coordination of the two. Previous literature has mainly focused on unilateral effects, such as the impact of green finance on technological innovation. However, this paper fills the gap by considering the concept of interaction. Third, our study examines the spatial agglomeration effect of the coupling coordination between green finance and technological innovation using the Moran index, which provides a novel perspective to the field. Finally, by analysing the coupling coordination of green finance and technological innovation, we highlight the urgency of strengthening green finance policies, promoting technological innovation, and mitigating regional development disparities, thereby guiding policy formulation.

The paper is structured as follows: the second part establishes the theoretical framework for the analysis and formulates the hypothesis. The third part develops the model and explains the variables and data. The fourth section calculates the degree of coordination between green finance and technological innovation. The fifth section examines the spatial impact and the sixth part discusses the results. Finally, conclusions and policy recommendations are drawn.

2. Theoretical Analysis and Research Hypothesis

1.1. Mechanism analysis of the coupling coordination between green finance and technological innovation

In a low-carbon economic system, green finance and technological innovation are indispensable components that are deeply intertwined and synergistic [7,8]. Specifically, green finance can facilitate technological innovation by easing financing constraints, promoting risk diversification and establishing information verification mechanisms. Technological innovation, in turn, allows green finance to be driven by demand pull, technology supply and return on investment effects.

1.1.1. Green finance supports technological innovation

Technological innovation is characterised by high input, significant risk, considerable profitability and positive externalities. Each stage of the technological innovation process requires the involvement of finance. Specifically, green finance supports technological innovation by easing financing constraints, diversifying risks, and implementing information verification mechanisms. First, green finance opens up avenues for technological innovation by alleviating financing constraints. By facilitating green enterprises through green finance, the costs associated with debt financing can be reduced, enabling these enterprises to access more bank loans and ultimately fostering technological innovation [9,10].Second,the risk diversification mechanism of green finance facilitates technological innovation. In the process of green technology innovation, there is a certain risk of failure, namely the possibility that scientific and technological advances may not be effectively translated into tangible productivity. However, various financial instruments and markets in the field of green finance can efficiently spread and transfer the risks associated with technology research and development towards industrialisation [11,12]. Third, the establishment of a green financial information review mechanism to promote technological innovation. This mechanism enables banks and other financial institutions to use their credit information systems and data processing capabilities to evaluate and identify projects with investment potential, track the cash flow status of enterprises, or assign supervisors to monitor the real-time green technology innovation process of investment enterprises [13,14]. As a result, such a review mechanism promotes the success of enterprises in green innovation.

1.1.2. Technological innovation drives green finance

Technological innovation drives green finance through demand pull, technology supply and return on investment effects. First and foremost, technological innovation drives the development of green finance through demand pull. In an innovation-driven approach, companies are vigorously cultivating industries focused on energy conservation, environmental protection, new energy and advanced

materials [15,16].The technology-intensive and strategic emerging sectors represented by these industries are in a phase of rapid growth, creating immense demand for green finance [17]. In order to meet the financing needs of various industries, this is driving the development of green finance and making it a new growth point for the future development of the financial sector. In addition, technological advancement increases the availability of technology, thereby facilitating the development of green finance.Technological innovation persistently translates scientific and technological advances into tangible productivity, especially enhancing the operational efficiency of enterprises and promoting technological progress and efficiency of the whole society, especially in rural areas. The integration of this technology into financial institutions escalates the productivity of green finance, consequently stimulating the development of green finance [18]. Finally, the advancement of green finance is promoted by the return on investment mechanism inherent in technological innovation.The active promotion of regional green science and technology innovation activities significantly contributes to promoting the development of green science and technology in universities and research institutes in the region, facilitating the implementation of green science and technology projects, and ultimately reducing production costs for enterprises and industries [19]. At the same time, innovation in green technology increases labour productivity, resulting in financial investments that generate incremental performance returns. The combination of low costs and high profits leads to a higher return on investment, facilitating the scaling up of green finance and the optimisation of its structure. Ultimately, this development fosters the growth of green finance.

In summary, the relationship between green finance and technological innovation is mutually influential: by using green finance, we can alleviate the financial constraints that hinder technological innovation, mitigate the risks associated with technological research and development, strengthen supervision, and facilitate technological innovation characterised by substantial R&D investment, long returns, and significant breakthroughs. Technological innovation, in turn, will stimulate firms' demand for capital, increase the efficiency of financial services, and induce financial institutions to achieve higher returns on investment. In other words, within the positive feedback loop, green finance and technological innovation may have reached an advanced stage of development and show a mutually reinforcing relationship, leading to a collective amplification effect. As a result, the following hypotheses are clarified.

Hypothesis 1. The coupling coordination between green finance and technological innovation is high.

1.2. The spatial spillover effect of coordination between green finance and technological innovation

Recently, an increasing number of researchers have examined the spatial spillover effects of green finance and technological innovation from the perspective of the "new geography" [20]. For example, some scholars have found that while green finance promotes regional economic development, it also has a positive spillover effect on other regions within the same area [21,22]. At the same time, some scholars confirmed that the influence of technological innovation on high-value economic development has a pronounced positive effect within the region, but a negative spatial spillover effect on surrounding regions with economic distance [16].In light of the existing research, it is posited that the synergistic integration of green finance and technological innovation may also exhibit spatial effects. The spatial effects are mainly characterised by two transmission mechanisms [23]. The first mechanism is a robust system coupling coordination within neighbouring regions, which generates a "spillover effect" that stimulates the development of the regional system through demonstration or driving influences, thereby enhancing the coupling coordination between different elements within the region. On the other hand, the strong coupling coordination relationship in neighbouring regions means a higher competitive advantage in resource acquisition, resulting in a "siphon effect" that hinders the development of relevant coupling coordination relationships within the region. On this basis, the following hypothesis is put forward.

Hypothesis 2. The coordination coupling between green finance and technological innovation exhibits a spatial effect.

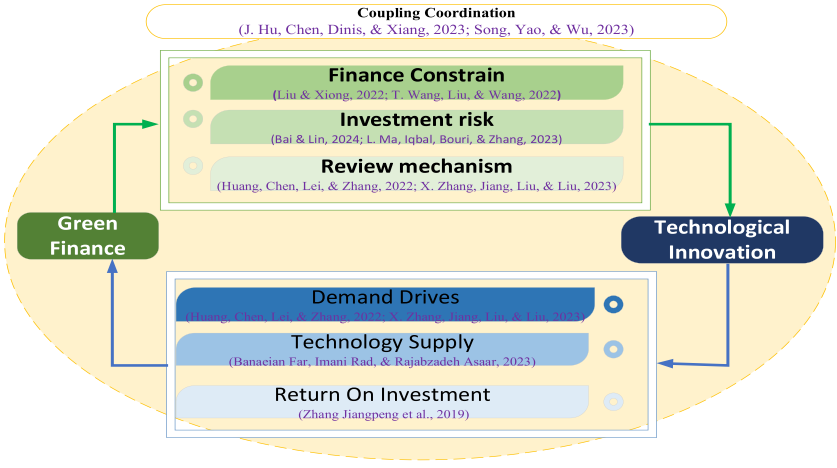

Fig. 1. Coupling coordination framework of green finance and technological innovation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

In summary, the framework of the coordination coupling between green finance and technological innovation can be expressed as shown in Fig. 1.

2. Materials and methods

2.1. Construction of an indicator system

According to the semantic and idiosyncratic characteristics of the relationship between green finance and technological innovation, while adhering to the principles of scientific rigour, integrity, taxonomy and operability, an index system quantifying the degree of coupling coordination between these two aspects was constructed, as shown in Table 1. Specifically, the sub-table system of the degree of coupling coordination between green finance and technological innovation is divided into two categories: green finance and technological innovation.

2.1.1. Green finance index

According to relevant studies on green finance [24–26], the subsystem of green finance consists of five components: green credit, green investment, green securities, green insurance and carbon finance. First, the green credit system requires financial institutions to consider factors such as resource conservation, pollution control, and environmental protection as essential considerations in their lending decisions. This system guides society as a whole towards minimal resource and energy consumption through the rational allocation of credit resources. The allocation of loans for environmental protection projects is communicated. Second, green investment refers to the investment made by companies to improve resource-saving and environmentally sustainable projects, as measured by the ratio of environmental protection investment to GDP. Third, the Green Securities Index is a comprehensive environmental protection assessment standard and evaluation method specifically designed for listed companies, which includes green market access, green capital issuance and rights issues, as well as an environmental performance disclosure system. This index serves as a proxy to measure the development of green bonds in this study. Fourth, the promotion of green insurance is closely related to the level of insurance development. Carbon finance refers to a series of activities carried out by financial institutions to facilitate the development of carbon finance, with the aim of serving their own interests, avoiding environmental risks and complying with national energy conservation and emission reduction policies. This can be illustrated by the Low Carbon Finance Index. The data included in the Green Finance Index system are mainly drawn from authoritative sources such as the websites of the National Bureau of Statistics, the Ministry of Science and Technology, the People's Bank of China and various authoritative statistical yearbooks.

2.1.2. Technological innovation index

According to relevant studies [27], the subsystem of technological innovation development is evaluated from two perspectives: input and output. On the one hand, the input of technological innovation serves as the basis for innovation activities, mainly manifested in human resources, financial investments, etc. In this study, the full-time equivalent of R&D personnel, the proportion of government science and technology allocation in fiscal expenditure, and the number of transferred teachers in higher education institutions are selected as evaluation indicators of technological innovation input [28]. On the other hand, technological innovation output measures the benefits derived from innovation activities, which can be reflected in the number of patents. In this study, the number of approved invention patents, the number of design patents, and the number of newly used patents are selected as the evaluation indicators for technological innovation output [29,30].The primary data are obtained from the CSMAR database, the China Statistical Yearbook, the China Regional Economic Statistical Yearbook, the China Science and Technology Statistical Yearbook, and the websites of provincial and municipal statistical offices.

Table 1
Coupling coordination degree model of green finance and technological innovation.

Subsystem	Measuring Metrics	Indicator Description
Green Finance (u_1)	Green credit	Proportion of loans for environmental protection projects = Total credit for environmental protection projects in the province/Total credit for the province
	Green investment	Environmental governance investment ratio = Environmental governance investment/GDP
	Green securities	Degree of green bond development = Total green bond issuance/Total bond issuance
	Green insurance	Environmental pollution liability insurance promotion degree = Environmental pollution liability insurance income/Total premium income
	Carbon Finance	Financial decarbonization level = Loan balance/Carbon emissions
Technology Innovation (u_2)	Innovation input	Full-time equivalent of R&D personnel (person-years)
		Local government expenditure on science and technology (100 million yuan)
		Total number of faculty and staff in institutions of higher learning (10,000)
	Innovation output	Number of invention patents granted (items)
		Number of appearance patents (items)
		Number of new patents in use (items)

[1] The data from the CSMAR database.

2.2. The assessment methods of coupling coordination

2.2.1. Degree of coupling coordination

Green finance and technological innovation are complex systems characterised by different structures and rich content. To better assess the degree of interaction or complementarity between the subsystems of green finance and technological innovation [31,32],the degree of coupling coordination is calculated based on the coupling coordination model using the following specific formulas:

$$C = \sqrt{\frac{u_1 \times u_2}{(u_1 + u_2)}} \tag{1}$$

$$D = \sqrt{C \times T} \tag{2}$$

$$T = a \times u_1 + b \times u_2 \tag{3}$$

In the formula, u_1 and u_2 symbolise green finance and technological innovation, respectively. In general, two systems are considered equally important if their respective contributions to the growth of the overall system do not differ significantly from each other, so a and b are 0.5 [33]. The value of D indicates the degree of coupling coordination, with a higher D indicating a greater degree of coupling coordination. In this paper, we refer to the existing literature [34,35], apply a broad range of quadratic methods, and divide the stages of coupling and coupling coordination into four stages: low coupling coordination ($0 < D \leq 0.2$), moderate coupling coordination ($0.2 < D \leq 0.5$), benign coordinated coupling ($0.5 < D \leq 0.8$), and highly coordinated coupling ($0.8 < D \leq 1$).

2.3. Relative level of development

Reflecting the coordinated development relationship between green finance and technological innovation, the coupling coordination does not effectively show the relative development level of these two aspects. Referring to the research results [36] that introduce the concept of relative development level (E), the model can be expressed as follows:

$$E = \frac{u_1}{u_2} \tag{4}$$

According to the classification results of the current literature [37], the coupled and coordinated development stage of green finance and technological innovation is divided into the lagging technological innovation stage of green finance ($0 < E \leq 0.8$), the synchronous technological innovation stage of green finance ($0.8 < E \leq 1.2$), and the superior technological innovation stage of green finance ($1.2 < E$).

3. Results

In accordance with the coupling coordination evaluation index system for green finance and technological innovation established previously, the entropy method was employed to compute the comprehensive indices of green finance and technological innovation from 2010 to 2021. Furthermore, coupling coordination level, and relative development degree were determined based on the comprehensive indices. The findings are as follows.

3.1. Level of coupling coordination

The level of coupling coordination between green finance and technological innovation is illustrated in Fig. 2. The coupling coordination index has increased from 0.05 in 2000 to 0.33 in 2021, reaching a qualitative change in 2012. In other words, after 2012, the coupling coordination development level of green finance and technological innovation has exceeded 0.2, indicating that they have entered a stage of moderate coupling coordination with an increased impact of interaction. Moreover, when we examine the coupling coordination development level across different regions, we find a significant disparity between the eastern, central and western regions.

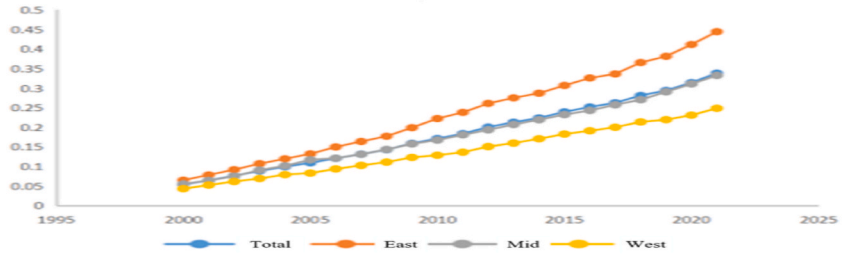

Fig. 2. Coupling coordination level from 2000 to 2021.

3.2. Relative development

Fig. 3 shows the relative development of the coupling coordination between green finance and technological innovation from 2000 to 2021. Overall, since 2000, China has followed a pattern where green finance precedes technological innovation. Therefore, efforts should focus on promoting the supply-side reform of green technology. Leapfrogging from imitative innovation to independent innovation in green technology can be achieved by training technical personnel and promoting high-quality green projects. Second, from a regional perspective, the relative development level of the western region is higher than the national average, with significant external influence, resulting in fluctuations.

4. Further analysis - spatial effect

4.1. Moran index

Following relevant studies [38,39], this paper uses the global Moran's I index to examine the spatial correlation of the coupling coordination between green finance and technological innovation, specifically whether there is a spatial dependence between provinces in terms of their coupling coordination and geographical location. If the resulting value is statistically significant and positive, it indicates a positive spatial correlation between the coupling coordination of green finance and technological innovation within each province; otherwise, it indicates a negative spatial correlation. The calculation for the global Moran index is as follows:

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(D_i - \bar{D}\right)\left(D - \bar{D}\right)}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(D_i - \bar{D}\right)^2} \tag{4}$$

In the formula, I represents the Moran index. D_i represents the degree of coupling coordination of each province in China, where n is the total number of 31 provinces. $\overline{D}$ represents the average value, while w_{ij} represents the spatial weighting matrix.

4.2. Spatial correlation test

Prior to conducting the spatial effect test, it is essential to conduct a spatial correlation test to investigate the coordination of green finance and technological innovation linkages. Following the current literature [40], the global Moran index is used to assess whether the spatial distribution under the geographical weight matrix shows spatial correlation. This analysis includes data from 31 provinces in China, covering the period from 2000 to 2021.The global Moran index, which assesses the spatial correlation of the coupling coordination between green finance and technological innovation, is examined, and the results are presented in Table 2. Due to the limitations of the length of this paper, the results for the last decade are discussed. Although the Moran index of coupling coordination between green finance and technological innovation is insignificant from 2000 to 2004, this does not completely rule out the possibility of spatial correlation during this period. Thus, the global Moran index for the coupling coordination of green finance and technological innovation in each Chinese province is above 0. The majority of these indices show statistical significance at the 1 % level, suggesting a notable spatial correlation in the coupling coordination.

4.3. Moran scatterplot analysis

To further elucidate the spatial aggregation pattern due to spatial constraints, this study presents a local Moran scatter plot that examines the coupling coordination of green finance and technological innovation in 2021, as shown in Fig. 4. The details of Fig. 4 are listed in Table 3.According to the results, a significant proportion of provinces in 2021 are located in the third and first quadrants, suggesting that the interplay between the levels of green finance and technological innovation has a pronounced local aggregation pattern.

Specifically, in the first quadrant (HH efficient clustering type), there are eight provinces, including Shanghai, Jiangsu, Zhejiang,

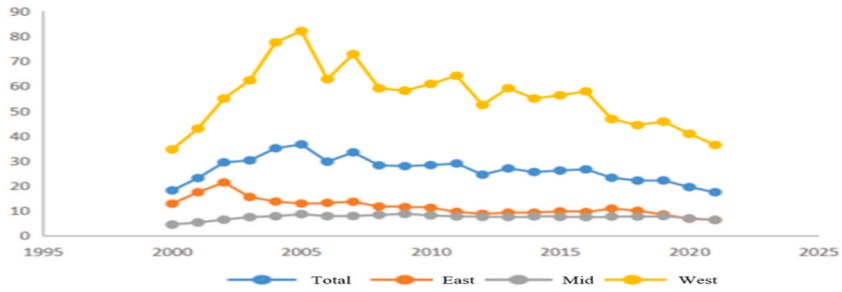

Fig. 3. Relative development degree from 2000 to 2021.

Table 2
The results for spatial correlation test.

	(1)	(2)	(3)
	I	P value	Z value
2012	0.084	0.001	3.436
2013	0.092	0.000	3.653
2014	0.093	0.000	3.658
2015	0.083	0.001	3.391
2016	0.089	0.000	3.152
2017	0.074	0.002	3.135
2018	0.074	0.002	3.152
2019	0.093	0.000	3.647
2020	0.084	0.001	3.440
2021	0.080	0.001	3.330

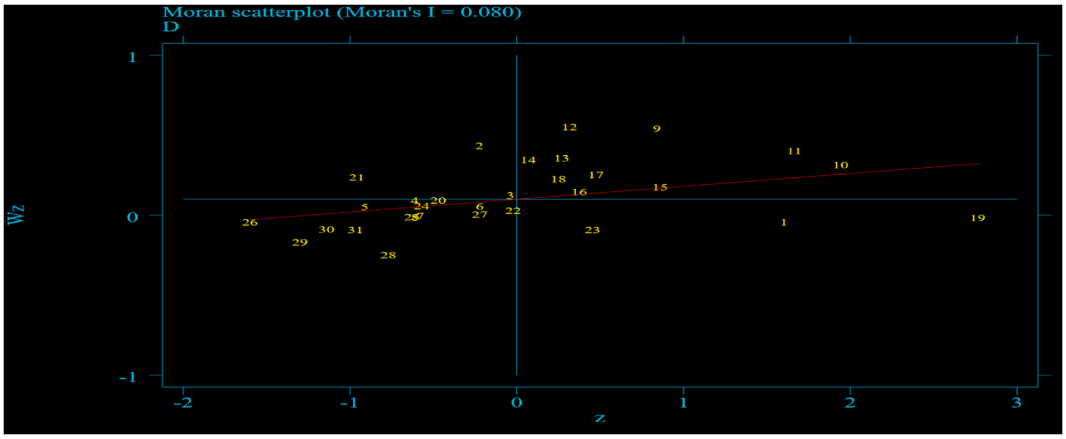

Fig. 4. Local Moran scatterplot of coupling coordination degree.

Table 3
The results for local Moran in 2021.

Quadrant	Province
First quadrant	Shanghai(9), Jiangsu(10), Zhejiang(11), Anhui(12), Fujian(13), Jiangxi(14),Shandong(15), Henan(16), Hubei(17), Hunan(18)
Second quadrant	Tianjin(2), Hainan(21), Hebei(3)
Third quadrant	Yunnan(25), Tibet(26), Shaanxi(4), Gansu(28), Qinghai(29), Ningxia(30), Xinjiang(31), Shanxi(27), Liaoning(6), Guizhou(24), Jilin(7), Heilongjiang(8), Chongqing (22),Inner Mongolia(5),Guangxi(20)
Fourth quadrant	Guangdong(19), Sichuan(23), Beijing(1)

Anhui, Fujian, Jiangxi, Shandong, Henan, Hunan and Hubei, accounting for 32.2 % of the national total. Among these provinces, the degree of coordination between green finance and technological innovation is high, and the spatial spillover effect is significant, driving the development of coordination in neighbouring provinces.

What's more, in the second quadrant (LH Inefficient Dissipation Type), there are three provinces, including Tianjin, Hainan and Hebei, accounting for 9.67 % of the national total. In this quadrant, the coupling coordination degree of green finance and technological innovation coupling is relatively weak, and the coupling coordination index of neighbouring provinces is usually high. For example, Tianjin province's neighbouring provinces, Beijing, are in the fourth quadrant of agglomeration level, but it has not absorbed its spatial spillover benefits, resulting in a low level of modernisation.

Third, there are 15 provinces in the third quadrant (LL inefficient cluster type), including Yunnan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, Shanxi, Liaoning, Guizhou, Jilin, Heilongjiang, Chongqing, Guangxi and Inner Mongolia.They are mainly located in the central and western provinces, accounting for 48.38 % of the country. Among the provinces in this quadrant, the degree of coupling coordination between green finance and technological innovation is low. The modernisation level of neighbouring provinces is also generally low, with a low-level clustering phenomenon, such as Qinghai, Gansu and Tibet.

Fourth, in the fourth quadrant (HL efficient dissipation type), three provinces including Guangdong, Sichuan and Beijing contribute 9.6 % of the national total. Despite the relatively high level of coordination between green finance and technological innovation in

these provinces, the spatial spillover effect is limited and thus fails to stimulate the development of neighbouring regions. For example, Guangdong Province, which has the highest level of low-carbon economy in the country, has a relatively low spillover effect. Strengthening communication and coordination between Guangdong Province and neighbouring regions, as well as establishing an integrated cooperation and development mechanism, would effectively promote the degree of coupling coordination of green finance and technological innovation.

In summary, the coupling coordination between green finance and technological innovation shows a remarkable positive spatial correlation, albeit at different levels of aggregation. In particular, the underdeveloped agglomeration of most western regions urgently needs to make use of its resource endowment advantages to improve the coupling coordination between green finance and technological innovation. At the same time, the eastern region should further strengthen its external synergies to facilitate the orderly development of the central and western provinces.

4.4. Robustness test

To ensure the stability of the regression results, we conducted separate tests on the replacement weight matrix and sample size [41]. First, we replaced the geographical distance matrix with the adjacency and economic weight matrices for computational purposes. The estimated coefficients of the neighbourhood weight matrix regression with economic weight were significantly positive, consistent with those obtained from the regression with the geographical distance matrix. This effectively verifies the robustness of our original estimation, as shown in columns one and two of Table 4. Second, given the significant differences in resource endowments between areas such as municipalities directly under the central government and other cities, we removed Beijing, Shanghai, Tianjin and Chongqing from our analysis, as shown in column three of Table 4. The results show only minor changes in the parameters, which are insufficient to support new findings. From this analysis it can be concluded that the research results presented in this paper are essentially robust.

5. Discussion

The present study uses a coupling coordination degree model to evaluate the interaction between green finance and technological innovation in 31 provinces in China from 2000 to 2021. The results show that there is a significant coupling coordination between green finance and technological innovation, although it is not as high as assumed in hypothesis 1. Specifically, the degree of coupling coordination has increased steadily over the years, with a notable shift since 2012. Before 2012, the main factors contributing to this situation were mainly attributed to relatively sluggish technological innovation.A low level of innovation input and consequently limited innovation output, as well as a lack of economic vitality [42]. In response to the problem, China quickly implemented the "4 trillion" stimulus package. At the same time, to facilitate policy implementation and support local governments in green financing [43], the central government eased restrictions on local financing platforms and bank loans, thereby promoting financial development and fostering innovation. As a result, initial achievements have been realised since 2012, leading to the coordinated development of green finance and technological innovation [44].

Moreover, the level of development related to different regions shows a significant disparity between the eastern, central and western regions. Compared with the mid and western regions, the financial development system in the eastern region has made significant progress, providing a wider channel for green finance resources to drive technological innovation [45]. In addition, the maturity of the market in the eastern region is more conducive to the development of green finance and further promotes technological innovation [46]. Therefore, the eastern region should strengthen support for technological innovation and green finance in the central and western regions, facilitate the exchange of talent, technology and capital among the three regions, and establish a sound cooperation mechanism.

For economically advanced developed countries, industrial development takes the lead internationally, with their economies driven primarily by high value-added factors such as innovation [47]. The coupling coordination of technological innovation and green finance is mainly driven by technological progress. In contrast, developing countries with relatively underdeveloped economies

Table 4
The results for robustness test.

	I		
	(1)	(2)	(3)
2012	0.236 * * *	0.241 * * *	0.083 * * *
2013	0.269 * * *	0.247 * * *	0.092 * * *
2014	0.291 * * *	0.291 * * *	0.103 * * *
2015	0.229 * *	0.244 * **	0.086 * * *
2016	0.274 * * *	0.249 * * *	0.093 * * *
2017	0.228 * *	0.235 * **	0.089 * * *
2018	0.232 * *	0.228 * **	0.082* * *
2019	0.293 * * *	0.237 * * *	0.102 * * *
2020	0.269 * * *	0.214 * * *	0.091 * * *
2021	0.273 * * *	0.213 * * *	0.086* * *

[1] Note: *, ** and *** indicate significance levels of 10 %, 5 % and 1 %, respectively.

rely heavily on foreign transfers for most industries [48], and due to a lack of core technology, the coupling coordination is mainly driven by green finance. Therefore, China's average relative development of linkage coordination is above one. Especially in the western region, where the level of green finance is significantly higher than the national average, this can be attributed to the lower level of innovation performance in the west. Going forward, it is crucial for the western region to continue to reform the financial industry in order to steadily promote technological innovation, ensure the steady development of the financial and real economy, prevent excessive financialisation, and strengthen financial safety and resilience.

From a spatial agglomeration perspective, there is a significant positive correlation between the coupling coordination of green finance and technological innovation, which strongly supports the second hypothesis. However, most western areas show a low level of concentration. Due to the relatively small economic volume and weak economic base, the western region relies heavily on industrial development and has limited financial and technological resources [49]. As a result, there is low concentration in the level of coordination between green finance and technological innovation, making the transition to a greener industry more difficult. In the long run, this discrepancy will lead to a significant gap with the eastern region, resulting in an exacerbation of the Matthew effect that hampers China's low-carbon development [50].

6. Conclusions and suggestion

6.1. Research conclusion

By establishing an evaluation index system and comprehensively employing the entropy method, coupling coordination degree model, and relative development degree model, this study assesses the coupling coordination between green finance and technological innovation in 31 provinces of China from 2000 to 2021, and investigates the spatial effects of such interplay. The detailed findings are as follows:(1)The coupling coordination between green finance and technological innovation exist. Utilizing the entropy method, coupling coordination degree model, and relative development degree model, this study examines the degree of coupling coordination between green finance and technological innovation. The findings reveal that: Green finance and technological innovation mutually promote and coordinate with each other, with the impact becoming increasingly prominent. Although the coupling coordination development trend between the two becomes increasingly prominent year by year. (2)The spatial impact of the coupling coordination between green finance and technological innovation is evident. From a spatial perspective, significant regional disparities are observed in the synchronization of green finance and technological innovation, with the degree of synchronization indicating that the eastern provinces and regions generally exhibit a higher level than their central and western counterparts, with the gap widening annually.

6.2. Research suggestion

Based on these findings, this study proposes three suggestions to promote the high-quality development:

First,the enhanced coordination of green finance and technological innovation should be prioritized.At present,the degree of coordination of green finance and technological innovation in China has increased,but the growth rate shows a fluctuating decline.To address this issue,it is imperative for the country to vigorously promote economic development, promote industrial structural upgrading, improve talent reserves, embrace international cooperation, reduce government intervention,and facilitate the coordinated development of green finance and technological innovation.

In addition, it is imperative to promote the harmonised development of green finance and technological innovation across regions. The level of coordination between green finance and technological innovation varies widely across regions in China, with a relatively weak state of coordination in western China.At the same time,the western region should leverage its inherent strengths to strengthen the level of coordination between green finance and technological innovation.

Third, strengthen resource allocation and policy support in the vicinity of "high-high" agglomerations to fully exploit the positive driving force of these areas in the eastern part of the country. What's more, this approach should be extended to the central regions for the development of backward areas, emphasising the positive characteristics resulting from the integration of all three regions and establishing an effective way to achieve sustainable green economic growth.

6.3. Implications

Theoretically, this paper will enhance the research on green finance and technological innovation. Existing studies mainly focus on confirming the unilateral promoting effect of green finance on technological innovation, with limited attention paid to exploring the correlation between the two from a cooperative perspective. This paper treats green finance and technological innovation as two complex subsystems and analyses their coupling degree of coordination and spatial effect. In doing so, it not only enriches the related research in both fields, but also expands the scope of systematics, thus providing a partial complementary role for academic research.

In practical terms, the paper offers practical strategies to effectively mitigate pollution and carbon emissions. As a major carbon emitter, China still relies heavily on fossil fuels in its energy structure. It is difficult to achieve the stable development of a low-carbon economy by administrative means and government intervention alone. Therefore, the coupling coordinated development of green finance and technological innovation has attracted considerable attention as a powerful approach to reducing pollution and carbon emissions. This study aims to assess the level of coordinated development between green finance and technological innovation, while analysing their spatio-temporal development patterns. The findings will provide valuable insights for promoting the coordinated development of green finance and technological innovation in different regions, thereby facilitating the formulation of specific policies

for carbon reduction.

6.4. Research limitations and future directions

The study has some limitations. First, the sample consists only of provincial data from China. Due to data availability constraints, the analysis only focuses on the coupling coordination of green finance and technological innovation in China. Therefore, future research should consider a broader sample to provide an international perspective to the discussion on the issue of coupling coordination. Second, the selection of regional science and technology innovation indicators in this paper draws on existing literature, while acknowledging the challenge of comprehensively measuring the level of regional science and technology innovation with a limited number of indicators. It also recognises that the connotation and definition of regional S&T innovation will evolve as scientific and technological progress continues. It is expected that future researchers will make significant breakthroughs in developing measurement indicators for regional S&T innovation. Finally, the research mainly focuses on the development level and spatial correlation effect of the coupling coordination degree between green finance and technological innovation, without addressing the influencing factors. It is expected that future scholars will delve into these influencing factors to further explore the coupled and coordinated development of green finance and technological innovation, and thus make targeted recommendations.

Data availability

Data will be made available on request to corresponding authors.

Ethical consent

A written ethical consent has been taken from the ethical committee at the Chongqing technology and business university, China, because the corresponding author is a lecturer at the university.

CRediT authorship contribution statement

Yi Li: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Bing Zhou:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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